"NSTAR Xenon Ion Thruster on DS1: Ground and Flight Tests"

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After having been in development for many years at Glenn Research Center (formerly
the Lewis Research Center), the NASA designed 30 cm ring-cusp xenon ion engine was
launched on the DS1 spacecraft on 24 Oct 98 from the Kennedy Space Center in Florida.
It has since accumulated 1800 hours of in-space thrusting at many different input power
levels and has successfully placed the spacecraft on a trajectory to fly by the asteroid
1992KD in July 99.

The design, assembly, test, integration, and operation of this thruster comprises a unique
path of technical determination, artful design choices, persistent engineering and analysis,
and mastery of vacuum chamber operations. The testing program over the development
years, the assembly and integration periods, and the flight operational period thus far has
shown that the project test philosophy of segregating effects against unique causes
proved itself most useful. The 8000 hour life test, the culmination of that ground test
plan, not only met its goals but surpassed them with margin.

This talk will explain the thruster test program from beginning to end, illustrating the
technical and programmatic decision making along the way. It will justify the use of
engineering models as an inexpensive method of determining answers to key design
questions and will explain why testing of the thruster alone only solved a portion of the
system operations task. The highlight of the test program proved to be the vacuum firing
of the ion engine during the spacecraft's solar thermal vacuum test.

We will conclude by comparing the pre-flight data with post-flight data to show that our
high confidence was warranted for executing a successful flight to the asteroid and
beyond.

1.0   Introduction to NSTAR

The NSTAR Project was started in 1992 to complete the development of an electric propulsion technology that had proved very promising in the laboratory for several decades, yet had never been included in a planetary or earth-orbital mission design. While there are several different forms of electric propulsion thrusters, the NSTAR electrostatic design originated in the 60's when Harold Kaufman proposed the first ion engine which used electrified grids and permanent magnets to accelerate ions to produce thrust. Early models of this thruster used Cesium or Mercury as propellant, and demonstration models were flown in 1964 and 197x on SERT I and II [2]. While these flights showed that we could operate such thrusters in space, they did not show that the thruster system could be built and tested with the reliability standards necessary for a flight mission, nor had they optimized the propellant itself to be suitable for use on delicate scientific spacecraft. Therefore, the NSTAR Project was conceived to validate this technology using a two pronged approach: a ground test program was aimed at validating the full lifetime of the ion engine for future missions while a flight test program had the objective of demonstrating the delivery, integration, launch, and operations of flight quality hardware and software. The overall objective of the entire effort was to produce the test and operational data that would allow a future spacecraft project manager to baseline this electric propulsion system, if it were the optimum solution for his/her mission, while confident that it was a flight proven technology.

This paper is organized into four sections. While this introduction explains NSTAR's background and introduces the test philosophy we used, the next sections lay out both parts of our test program for the thruster, then section 4 explains the operational data that we have collected during our present mission and its relation to the thruster performance we saw on the flight hardware before launch. Our paper does not cover the design details of the thruster, which have been amply documented in many of the referenced papers. We concentrate herein on the test program for the thruster and how that program led to a successful flight.

1.1   Project Structure & Teaming

Due to the decades long involvement by both organizations, NASA HQ determined that the NSTAR Project would be implemented through a team effort between the Jet Propulsion Laboratory (JPL) and the NASA Lewis Research Center (now the Glenn Research Center (GRC)). Both NASA Centers brought unique strengths to the Project. JPL brought its long history of managing spacecraft flight projects from inception through operations and its proven system engineering expertise, and GRC brought its thruster development and design history plus the outstanding thruster testing facilities in Cleveland. Together with industrial partners to build the flight hardware, this joint team set out to implement the NSTAR plan.

1.2   Ground Tests

A ground test program was planned which included the use of Engineering Model Thrusters (EMT). The EMT design was based on an evolving design at the GRC whose features had been incrementally tested during the 80's within their propulsion technology charter. Factors such as grid erosion, sputter containment, heater life, discharge efficiency, propellant suitability, and cathode design had all been explored over the years, and all such investigation results had culminated in a 30 cm. ring-cusp design that was proposed as the most satisfactory compromise between power level, thruster efficiency, and lifetime for the NSTAR validation task. That initial design was used to build several evolutionary engineering model thrusters which would serve as the project's test units until flight units were available. The biggest question to be answered immediately was whether the analytical lifetime prediction for the thruster as a whole would prove to be true with the

individual features proposed and tested over the long development period. The ground tests explained in the next section were meant to answer this lifetime issue in time for the flight units to be built, tested, and flown.

1.3 Flight Unit Tests

It had to be assumed, for schedule purposes, that the EMT design would prove itself satisfactory. Since we were not confident of an accelerated method to verify the thruster lifetime, the tests were to be full-scale and real-time. This meant that the effort to mold our EM design into a robust flight quality design had to start and be conducted in parallel with those very tests that were proving the quality of the basic design. Figure 1-1 illustrates how our industrial contractor started his upgrade task well before our lifetime question had been verified. We viewed this allowance as acceptable because we realized that certain upgrades were going to be required, such as increasing the number of mounting points from 2 to 3, regardless of the thruster's other design details.

The flight unit test portion of the program was also faced with formidable issues. While chemical thrusters typically have relatively few parts, an electric thruster, in this case the GRC design, may consist of 100's of parts. The first challenge for the thruster contractor, Hughes Electrodynamics Division (HED) of Torrance, CA, was to modify the basic thruster design with flight quality upgrades so that it could withstand the rigors of a launch vehicle, all within a mass goal of 8 kg. The qualification of such a complex, configurationally dispersed piece of hardware could have proved troublesome. These flight model tests are explained in section 3.

1.4 Thruster Performance

The GRC thruster proposed for NSTAR development was a 30 cm, ring-cusp, 10 kW, xenon ion bombardment thruster, derated to 2.5 kW. See Figure 1-2 for an illustration of some of the thruster's features. The most unique aspect of the system was that the thruster could be throttled anywhere between power levels of 500W and 2500W. These levels correspond to thrusts of from 21 mN to 92 mN; therefore, depending on the solar array power available, NSTAR can be set to use as much power as the spacecraft can spare. This feature is especially valuable when a mission trajectory is receding from the sun and power is steadily decreasing. Since thruster efficiency is directly proportional to power level, a mission designer would be reluctant to waste any available power for thrusting, and a throttleable engine is a valuable tool to maximize propellant efficiency for the mission. Table 1-1 shows a basic set of thruster parameters for a discrete number of power levels. With the xenon feed system that flies with the NSTAR thruster, it should be noted that any power level between 500W and 2500W is available to the mission designer - the list shown is by no means unique, though power levels separated by < 20W begin to encroach on the uncertainties in the telemetry sensor calibration levels and the ability to measure spacecraft power margins.

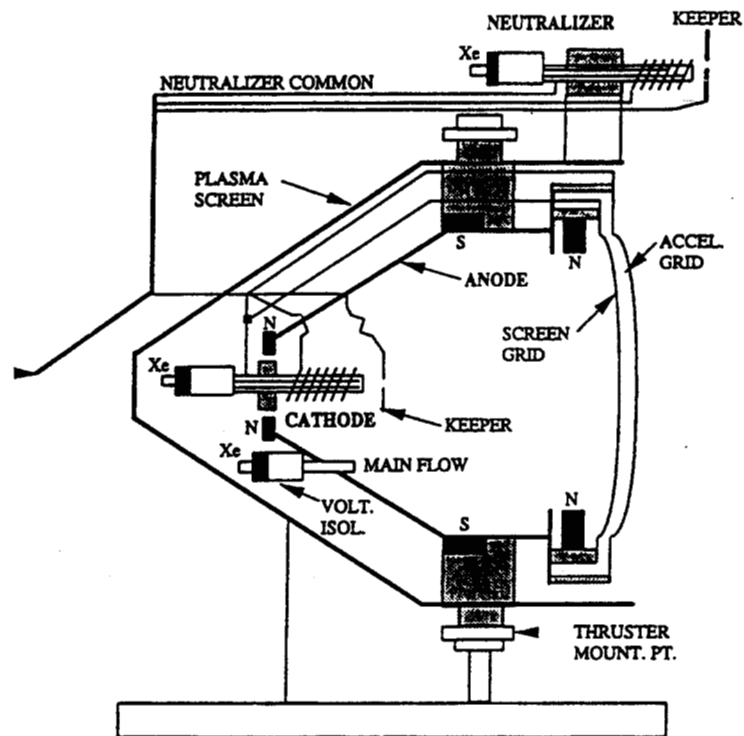| NSTAR Throttle Level	Mission Throttle Level	Beam Supply Voltage (V)	Beam Supply Current (A)	Accelerator Grid Voltage (V)	Neutralizer Keeper Current (A)	Main Plenum Pressure (psia)	Cathode Plenum Pressure (psia)
15	111	1100	1.76	-180	1.5	87.55	50.21
14	104	1100	1.67	-180	1.5	84.72	47.50
13	97	1100	1.58	-180	1.5	81.85	45.18
12	90	1100	1.49	-180	1.5	79.29	43.80
11	83	1100	1.40	-180	1.5	76.06	42.38
10	76	1100	1.30	-180	1.5	72.90	41.03
9	69	1100	1.20	-180	1.5	69.80	40.26
8	62	1100	1.10	-180	1.5	65.75	40.26

Figure # - Schematic of the NSTAR Ion Thruster

1-2

NSTAR Overview Schedule

AT - Acceptance Test
FT - flight thruster
FP - flight PPU

■ functional integrations

| CY93 | CY94 | CY95 | CY96 | CY97 | CY98 | CY99 |

New Millennium Spacecraft Schedule

box fab/test
sys test
lch ops
prototyping
SAI build JPL integ
S/C IDC
S/C DDC
launch

GROUND TEST

EM Thrusters
dispersion tests
#2 #3 #4
XFS
Flt Units

BB Power Processing Unit
design
fab #1

Life tests @ LeRC,JPL,&Industry
prelim plume
Life Demo Test
Extended Life Test

Characterization & Dev. tests

FLIGHT PROGRAM

Thruster Element
tst spt D&D FT fab/assy PFT, #1
test PFT
RFP out contract award
PFT #1

BB
FP fab/assy #1, #2
test #1 #2
Element PDR
Element CDR
#1 #2

Qual Environment tests
AT

Flight Integration & acceptance tests
Delivery to S/C

Feed system
XEM1 test
tst spt design pcrmnts assbly
contract award PDR CDR Delivery to S/C

Diagnostics system
hardware develp component integ ODR
Delivery to S/C s/s environmental final cal

Today

23 Mar 99

Figure 1-1

7	55	1100	1.00	-150	2.0	61.70	40.26
6	48	1100	0.91	-150	2.0	57.31	40.26
5	41	1100	0.81	-150	2.0	52.86	40.26
4	34	1100	0.71	-150	2.0	48.08	40.26
3	27	1100	0.61	-150	2.0	43.18	40.26
2	20	1100	0.52	-150	2.0	39.22	40.26
1	13	850	0.53	-150	2.0	39.41	40.26
0	6	650	0.51	-150	2.0	40.01	40.26

Table 1-1: Flight throttle table of parameters controlled by the DCIU

When a start command is given to the NSTAR system, our electronics first pressurizes the feed system to the correct level, then starts the neutralizer cathode and main cathode in that order, and lastly, once cathode operation is verified, applies high voltage to the thruster optics to produce thrust. Subsequent throttling to higher or lower power levels when commanded does not involve interrupting operations. Again, the electronics configures the feed system properly then smoothly shifts the discharge power level to the commanded operating point, which in turn determines the beam current. Thrusting continues in a continuous, uninterrupted manner.

1.5 Mission
In 1995, the NSTAR Ion Propulsion System was proposed as the primary propulsion system for the New Millennium Program's first mission, Deep Space 1 (DS1). This milestone selection was made when the New Millennium Program was created by NASA to demonstrate technologies which, while of tremendous importance for future missions, were not flight-proven. NSTAR was only one of 12 different technologies selected for the DS1 spacecraft, another being the radical new solar array, SCARLET. Since the NSTAR system could consume 2500 W by itself at maximum thrust, producing enough power for both the engine and the spacecraft would be one of SCARLET's challenges.

The flight system for NSTAR consisted of the Flight Thruster (FT), a Power Processing Unit (PPU), a Digital Control Interface Unit (DCIU), a Xenon Feed System (XFS), and the Ion Diagnostics System (IDS). (do we need a figure for this??)

Our minimum success criteria during the DS1 flight was to generate operational data for 200 hours of thrusting. Once DS1 was successfully launched on 24 Oct 98 and thrusting was initiated on 10 Nov., that goal was quickly accomplished, much to the satisfaction of the Project Team. Since that time, 1800 hours of thrusting (non-continuous) enabled a very successful fly-by of the asteroid Braille on 29 July 99, and further thrusting is placing the spacecraft on a trajectory to encounter the comet Wilson-Harrington in Jan 01. By that time, we shall have accomplished well over 11000 hours of thrusting and have consumed nearly 67 kg. of xenon. Figure 1-3 illustrates the mission plan.

1.6 Test Philosophy
The listing of ground tests which awaits the reader in the next section is long. It reflects a test discipline instituted early in the NSTAR Project which was born from the experiences of the electric propulsion groups at both our partner centers. Put simply, we stressed testing single issues at a time. Since the wear mechanisms of our thruster have not been completely modeled to this day (one of many sub-objectives of NSTAR) and the effects of multiple design changes on grid wear and depositions, etc. were often difficult to separate from one another, we made a conspicuous effort during our investigations to produce effects which we could attribute to single design modifications. Section 2 explains in more detail the issues which faced the NSTAR team after our first ground test and why this philosophy proved valuable in our path to a final thruster design.

2.0 The NSTAR Ground Test Program

The ground tests shown on Figure 1-1 were not entirely part of the original NSTAR plan. When the initial 2000 hour test was interrupted mid-point because of an isolator failure, the issue was quickly resolved and the test completed, but the inspection of the thruster at completion showed evidence of more erosion and depositions than were expected. Full details of this test were documented in reference 3. At that point, however, it was realized that several more development tests were going to be necessary to investigate a series of small design changes that were proposed. A series of Development Tests (DT) were initiated which are explained later in this section. Even after that series concluded, other issues continued to need resolution as different specific design questions arose during the time the Hughes contract was signed and our initial technical discussions began. We found the need for further Engineering Development Tests (EDT) which generally involved the thruster alone and, in addition, several Characterization Tests (CT) which we defined as involving two or more system components. These terms were strictly internal project definitions which we used for convenience.

Strictly speaking, then, our original planned test series consisted of:
NSTAR Project Test (NPT) 1 - the 2000 hour test,
NPT 3 - an 8000 hour life test, and
NPT 4 - a 12000 hour life qualification test.
Before we eventually felt confident in starting NPT3, however, our testing history was to encompass all the testing in the following sections' Tables. The relationship of these tests to our project design issues are all discussed in the succeeding sections.

2.1 Project Level Tests
When starting out, the NSTAR plan was intended to complete the lifetime validation of the thruster before the launch of DS1. That meant concluding NPT4 before Oct 98. Figure 1-1 reflects the actual accomplishment of events, showing that we fell far short of that goal. When the results of NPT3 are discussed later, the reasoning for this extension in testing can be understood. Table 2-1 summarizes the conduct of all the NPTs, though discussion herein will not cover every test listed. It should be noted that the duration column reflects actual thruster high voltage time, not length of the entire test.

Table 2-1   NSTAR Project Tests

TEST	Purpose	Description	Thruster	Duration	Location
NPT 1	Wear	first 2K	EMT1	867	GRC 5
NPT 1A	Wear	finish 2K	EMT1	1163	GRC 5
NPT 2a	FIT "A"	PPU integration test	EMT2	21	GRC 5
NPT 2b	FIT B	PPU integration test	EMT3a	12	GRC 5
NPT 3	LDT	Life Demonstration Test	EMT2	8194	JPL 148
NPT 4	ELT	Extended Life Test	FT2	5200+	JPL 148

•NPT1   As the first project level test to validate the quality of the EMT design, this 2000 hour test was meant to extend any previous life testing on designs of our type by a factor of two. The time scale was long enough to show evidence of deposition and erosion of thruster components yet short enough to produce results before the flight unit contractor proceeded too far into his activities. Both NPT1 and NPT3 were to be run at the full power level of 2.3 kW into the thruster under the assumption that the life limiting physical processes are worst at high power. The test reached 867 hours before being terminated because of a failed high voltage isolator on the thruster which prevented the proper xenon flow to the discharge chamber. Once this problem was diagnosed and

rectified, we were able to continue testing to completion. Examination of the thruster upon breaking vacuum, however, is what led to a substantial change in our testing plan.

Though the thruster exhibited good performance and stable operation throughout the 2000 hours, it is a function of this technology that its performance is not a reliable measure to detect physical degradation. Taken to the extreme, macro effects, such as exhibiting more power input to maintain a commanded thrust level, will be apparent in telemetry data and will indicate long term wear, but there are levels of erosion in the accelerator grid, for example, which can be tolerated by this thruster that will not reflect itself in its performance data. For the relatively short time period (with respect to predicted thruster lifetime) for this test, then, the physical inspection at the end of the test, including destructive physical analysis of the grids and cathodes, was critical to analyzing its true lifetime trends.

This analysis showed that we were not ready for flight with our original design. We discovered higher screen grid and cathode erosion than expected and more discharge chamber deposition than expected. In planning for individual design resolutions, the DT series was conducted to validate our ideas. Table 2-2 summarizes the test time which was accumulated during the DT series and the reasons for each test. DT15 was the last of the series and served as a final, reasonable duration validation of all the design changes which were to be incorporated in the 2nd EM thruster, EMT2. These modifications and the detailed reasoning behind each is explained in reference 4. Planning, setting up the proper facility, and conducting this full series took from Nov 94 to Oct 95, illustrating the direct, series effect to our test schedule of the remedial design effort resulting from the NPT1 observations. Note that a total of almost 2400 thrusting hours were devoted to our problem solution set.

Table 2-2   NSTAR Development Tests

TEST	Purpose	Description	Thruster	Duration	Location
DT 1	erosion rate	floating & grounded Screen Grid	EMT1	37	GRC 5
DT 2	erosion rate	grounded SG	EMT1	50	GRC 5
DT 3	erosion rate	floating SG	EMT1	51	GRC 5
DT 6c	technq accuracy	floating SG - measurement accuracy	EMT1	.25+	GRC 3
DT 7	mass loss	grounded SG	EMT1	100	GRC 3
DT 16	performance	new grids, backup badges	EMT1a	12	GRC 3
DT 9c	low power perf.	@ low power w/ margin testing	EMT1a	168	GRC 3
DT 18	perf & margins	2nd part of old DT 17	EMT1b	50	GRC 5
DT 8a	facility check	with flow sensitivity	FMT	21	JPL148
DT 9b	low power perf.	@ low power w/ margin testing	FMT	870	JPL149
DT 15	Revalidation	side welded main cathode + mesh	EMT1b	1011	JPL148
DT 19	chamber check	replaces DT 17a	j-series	24	JPL148

• NPT3   After such a deliberate and lengthy effort to redesign our thruster, vindication had to await the completion of the full 100% lifetime test, NPT3. Two issues would further serve to postpone this knowledge: preparations and duty cycle.

Because of a project resolve to account for all non-thruster related issues that could prematurely end (defined as breaking vacuum before 8000 hours of thrusting had been completed) our life test, the preparation period for NPT3 also served to delay our original timeline. Among other activities deemed as critical, we replumbed all tubing carrying liquids inside the chamber from compression fittings to welded joints. This is only a single example of why the interval between the end of DT15 and the start of NPT3 (Note that the same testing chamber was used for both.) took more than 7 months.

Practical considerations of operating vacuum chambers then allow far less than 100% duty cycle in these type tests. Reference 5 is a valuable summary of the conduct of this test and notes that our achieved duty cycle over the 17 months to completion was 72% (defined as thrusting hours divided by 168 hours per week). Though there were many shutdowns, none were related to thruster operation, and we achieved one of our prime goals of never breaking vacuum during this test.

Once physical analysis of the EMT2 thruster was initiated in Oct 97, preliminary results were quickly recognized as better than expected. A judgment had to be made whether the design features then being incorporated into the HED thrusters were safe for the DS1 mission. An analysis of thruster lifetime using the EMT2 measured post-test parameters showed almost a 16000 hour prediction – the go-ahead was given for the flight units with confidence that the results of NPT4 would later confirm our analyses.

2.2 CTs

During the time that NPT3 was being conducted, further questions were being resolved by the CT series. 39 tests were proposed relevant to system operation as opposed to thruster performance. There were many interface issues which deserved direct measurement as early in the development cycle as possible, and a cooperative effort between DS1 and NSTAR personnel gathered the EM equipment and simulators as soon as they were all available. Many of the tests on the list were alternatives based on the results of a previous test, so there was no intention to conduct them all, and the actual series is shown in Table 2-3. Deserving special mention are CT31b and CT36c.

• <u>CT31b</u>   With a 2.5 kW load being driven, the stability of the spacecraft power system deserved an early proof. Bringing together EM hardware and software from both NSTAR and DS1, an end-to-end system firing was demonstrated in Jun 97 with no stability problems evident. We covered a large range of input voltages to the PPU and the entire power range for the thruster and found more problems insuring the test set-up was properly grounded than in any system stability issue. This test is, nevertheless, recommended for any future program using such high power, non-linear loads on their power system.

• <u>CT36c</u>   A technical issue arose when considering how to conduct a solar thermal vacuum test (STV) for the spacecraft, which required 100 hours of IPS operation, because firing an engine for that long was impractical. A concept was proposed which eliminated the need for an engine thermal simulator, which we felt was very complicated to design. The concept consisted of lighting the two cathodes alone without applying high voltage to the grids, which was called "diode mode". We proved that this mode was thermally representative in the EDT thermal tests shown in section 2.3. It was operationally necessary, however, to drive the thruster with a power supply independent of the PPU. To demonstrate that the concept was safe for such an important test as STV, we re-configured the CT31b hardware with a separate thruster power supply and fired EMT4 successfully for an hour while monitoring all xenon flows and input power levels. Once we confirmed that all timing and parameter levels were correct, diode mode was approved for STV.

Table 2-3   NSTAR Characterization Tests

Thruster	TEST	Purpose	Description	Duration	Location
EMT1b	CT1	plasma screen grounding		~4	GRC 5
EMT2	CT19'-1	pre-transport sensitivity	abbreviated TP - only 2 op points	12.2	GRC 5
	CT18	AC frequency components		n/a	JPL148
	CT13	magnetic map	various distances from	n/a	JPL233

			thruster		
	CT19'-2	pre-LDT sensitivity		~5	JPL148
EMT3	CT5	low flow start - 3 sccm		~1	GRC 5
	CT6	single plena		~4	GRC 5
	CT14	empirical thermal measmts	part of EDT2b	~9	GRC 5
	CT22b	measure PPUin power quality	BBPPU during recycle	~8	JPL148
	CT27b	PPU input impedance		~2	GRC 5
EMT4	CT31b	system ETE power stability	includes HVPCU	~25	JPL149
	CT36b	SAS IF verification		~16	JPL149
	CT36c	diode mode trial		1	JPL149
SPOT	CT31b	system ETE power stability	includes HVPCU	n/a	JPL149
n/a	CT33	DCIU-XEM1 c/o		n/a	JPL233
SPOT	CT22a	same as CT22b	BBPPU during recycle	n/a	JPL148
SPOT	CT24	PPU start circuit	effects on DS1	n/a	GRC 5
SPOT	CT27a	PPU input impedance		n/a	GRC 5

2.3 EDTs

Thruster design was still an issue as the DS1 design firmed up and the NSTAR Project was exposed to their specified environmental requirements, especially the thermal conditions resulting from a DS1 decision to isolate the thruster from the spacecraft interior. Fabricating a spacecraft simulator and instrumenting EMT3 allowed a series of incremental thermal tests where the magnet temperatures were of most interest. It was this series that convinced our designers to stabilize the samarium-cobalt magnets at 350 ^{0}C instead of the original 250 ^{0}C.

Table 2-4   NSTAR Engineering Development Tests

TEST	Purpose	Description	Thruster	Duration	Location
EDT1a	initial vibe		EMT1b	n/a	NTS
EDT1b	follow-up vibe	with 3rd mounting pt	EMT1c	n/a	NTS
EDT1c	TGA vibe @ .2 g2/Hz	practice for FT#1	EMT1d	n/a	JPL144
EDT2a	cold start, etc	downstream open	EMT3a	~30	GRC 5
EDT2b	2nd phase thermal	+ downstream cover	EMT3a	~30	GRC 5
EDT2c	3rd phase thermal	+ gimbal sim plate	EMT3b	~34	GRC 5
EDT2d	4th thermal	+ DS1 thermal shield	EMT4	~30	GRC 5
EDT2e	final thermal	same as 2d	PFT	~30	GRC 5
EDT5	thrust stand performance	w/ modified ExB	EMT3	~6	GRC 5
EDT6	500 hr cathode erosion		EMT3	500	GRC
EDT7a	Internal B field		EMT3	n/a	GRC
EDT9	mesh separation		EMT4	~5	GRC
EDT12	screen grid saturation		EMT3	~6	GRC
EDT16a	shorted discharge keeper		EMT3	~2	GRC
EDT20a	plume tests		EMT3	~6	GRC

3.0 Flight Unit Test Program

Acceptance and Proto-flight qualification programs for the thruster element are shown in Figures 3-1 and 3-2, and the firing times for the thrusters are summarized in Table 3-1. Every effort was made to minimize the flight thruster operating time before launch because any deposition in the discharge chamber has a high probability of spalling after subsequent exposure to air, and we chose to minimize this possibility. We changed the grids on FT1 after its first performance test to a set with a higher perveance limit, so the total test time on the flight thruster at launch shows as 52.8 hours from the table.

Table 3-1	NSTAR Flight Thruster Testing		as of:	18 Aug 99
Thruster	TEST	Purpose	Duration	Location
PFT	s/c vibe	system level vibration	n/a	JPL144
	s/c pyro	system level shock	n/a	JPL144
	s/c STV	solar thermal vacuum	(87.5)	JPL150
	ICT	s/c compatibility	37 min.	JPL150
FT1	FT1 PAT	initial performance	15.2	GRC 5
	FT1b PAT	performance	11.4	GRC 5
	PFQ	thermal cycles	29.5	GRC 5
	AT vibe	.1 g2/Hz	n/a	JPL144
	FT1b PAT	post vibe performance	11.9	JPL148
	DS1	in flight	2200+	
FT2	Functional	pre vibe performance	21.7	GRC 5
	AT vibe	.1 g2/Hz	n/a	JPL144
	PAT	post vibe performance	14	GRC 5
	AT	thermal cycles	16.4	GRC 5
	Functional	final performance	5.8	GRC 5
	ELT	life qual - on-going	5200+	JPL148

The Pathfinder Thruster (PFT) was used for the entire DS1 system test program and then refurbished into FT2 in April 98 for the remainder of the 2nd units' acceptance test program. As can be seen, the total operating time on these new grids before entering the Extended Life Test was 57.9 hours.

End-to-end system performance was ultimately demonstrated in the IPS Compatibility Test (ICT) in Feb 98 when the engine was fired for short periods of time at low, middle, and high power levels in the thermal vacuum chamber using the spacecraft command and data system for thruster commanding. Several precautions were taken to protect the facility from backsputtered material during even such a short firing. For example, the solar simulator mirror was covered and a carbon grafoil target was placed in front of the engine to protect the chamber walls. Even so, an RGB monitor was installed to check for carbon content while firing, and once a faint level was detected, we terminated the test. All spacecraft systems performed normally during the firing, even through several recycles where the power level changes dramatically for fractions of a second. This eliminated any remaining EMI concerns with the system design.

Performance data from the FT1 tests were used to construct the Beginning-Of-Life (BOL) Throttle Table for DS1 which was shown as Table 1-1. Comparisons of this data to flight are shown in section 4.

The ELT will be the last test in the NSTAR program.
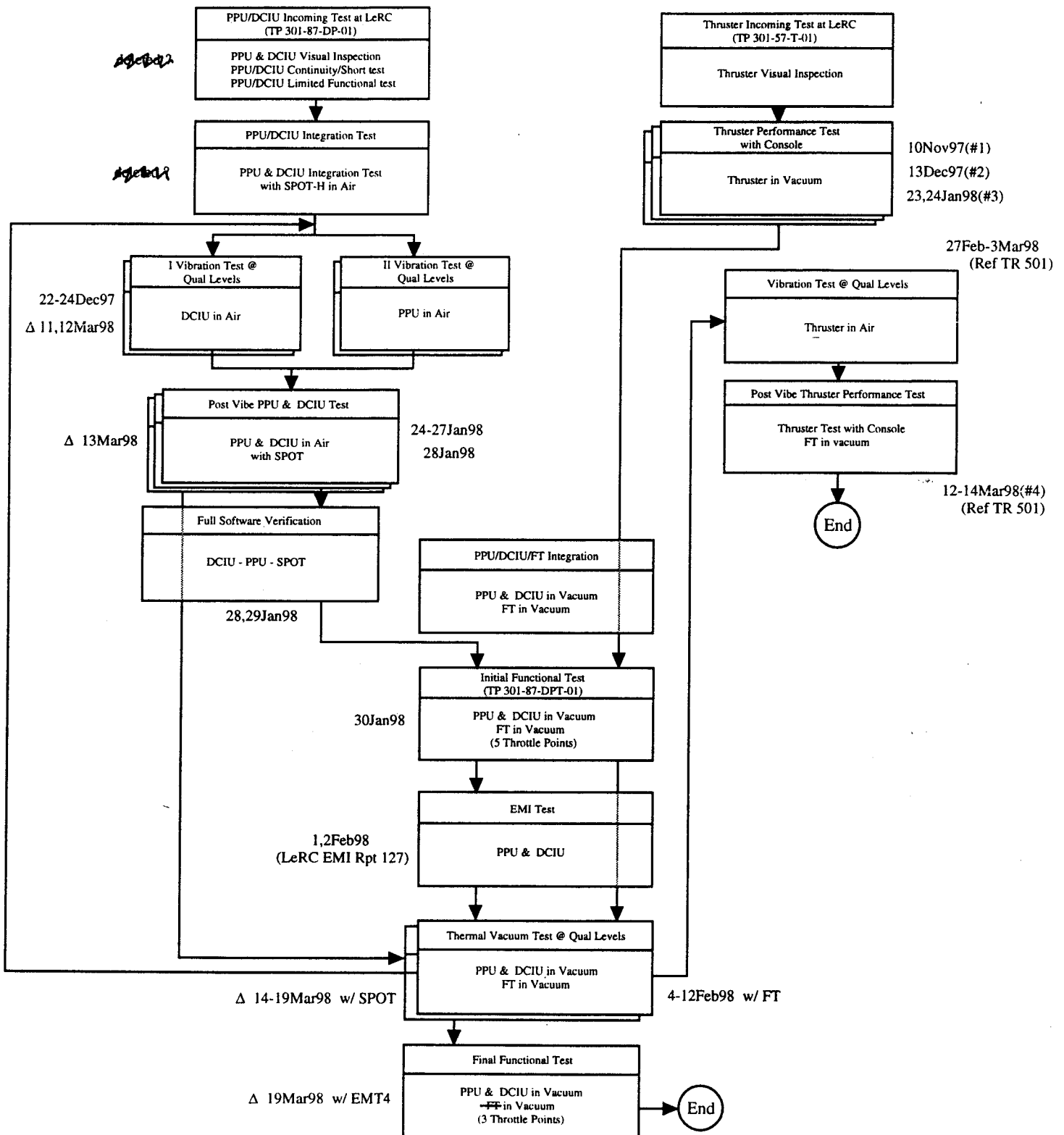
PPU2, DCIU2, FT1b

(Source: John Hamley, LeRC)

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┌─────────────────────────────────────┐          ┌─────────────────────────────────────┐
│  PPU/DCIU Incoming Test at LeRC       │          │  Thruster Incoming Test at LeRC       │
│       (TP 301-87-DP-01)               │          │       (TP 301-57-T-01)                │
│─────────────────────────────────────│          │─────────────────────────────────────│
│  PPU & DCIU Visual Inspection         │          │  Thruster Visual Inspection           │
│  PPU/DCIU Continuity/Short test       │          │                                       │
│  PPU/DCIU Limited Functional test     │          │                                       │
└─────────────────────────────────────┘          └─────────────────────────────────────┘
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19Feb02

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┌─────────────────────────────────────┐          ┌─────────────────────────────────────┐
│        PPU/DCIU Integration Test      │          │   Thruster Performance Test           │
│─────────────────────────────────────│          │         with Console                  │
│  PPU & DCIU Integration Test          │          │─────────────────────────────────────│
│      with SPOT-H in Air               │          │   Thruster in Vacuum                  │
└─────────────────────────────────────┘          └─────────────────────────────────────┘
```

10Nov97(#1)

13Dec97(#2)

23,24Jan98(#3)

27Feb-3Mar98
(Ref TR 501)

```
┌──────────────────────┐   ┌──────────────────────┐          ┌─────────────────────────────────────┐
│  I Vibration Test @   │   │  II Vibration Test @  │          │   Vibration Test @ Qual Levels        │
│    Qual Levels        │   │    Qual Levels        │          │─────────────────────────────────────│
│──────────────────────│   │──────────────────────│          │   Thruster in Air                     │
│    DCIU in Air        │   │     PPU in Air        │          └─────────────────────────────────────┘
└──────────────────────┘   └──────────────────────┘
```

22-24Dec97

Δ 11,12Mar98

```
┌─────────────────────────────────────┐          ┌─────────────────────────────────────┐
│       Post Vibe PPU & DCIU Test       │          │   Post Vibe Thruster Performance Test │
│─────────────────────────────────────│          │─────────────────────────────────────│
│     PPU & DCIU in Air                 │          │   Thruster Test with Console          │
│        with SPOT                      │          │        FT in vacuum                   │
└─────────────────────────────────────┘          └─────────────────────────────────────┘
```

Δ 13Mar98

24-27Jan98

28Jan98

12-14Mar98(#4)
(Ref TR 501)

(End)

```
┌─────────────────────────────────────┐          ┌─────────────────────────────────────┐
│       Full Software Verification      │          │      PPU/DCIU/FT Integration          │
│─────────────────────────────────────│          │─────────────────────────────────────│
│      DCIU - PPU - SPOT                │          │   PPU & DCIU in Vacuum                │
└─────────────────────────────────────┘          │        FT in Vacuum                   │
                                                   └─────────────────────────────────────┘
```

28,29Jan98

```
┌─────────────────────────────────────┐
│       Initial Functional Test         │
│       (TP 301-87-DPT-01)              │
│─────────────────────────────────────│
│   PPU & DCIU in Vacuum                │
│       FT in Vacuum                    │
│      (5 Throttle Points)              │
└─────────────────────────────────────┘
```

30Jan98

```
┌─────────────────────────────────────┐
│             EMI Test                  │
│─────────────────────────────────────│
│         PPU & DCIU                    │
└─────────────────────────────────────┘
```

1,2Feb98
(LeRC EMI Rpt 127)

```
┌─────────────────────────────────────┐
│   Thermal Vacuum Test @ Qual Levels   │
│─────────────────────────────────────│
│   PPU & DCIU in Vacuum                │
│       FT in Vacuum                    │
└─────────────────────────────────────┘
```

Δ 14-19Mar98 w/ SPOT

4-12Feb98 w/ FT

```
┌─────────────────────────────────────┐
│         Final Functional Test         │
│─────────────────────────────────────│
│   PPU & DCIU in Vacuum                │
│      ~~FT~~ in Vacuum                 │
│      (3 Throttle Points)              │
└─────────────────────────────────────┘
```

Δ 19Mar98 w/ EMT4

(End)

Figure 4.1.   IPS TE Qualification Test Plan

3-1

Figure 3-2
Figure 111
NSTAR/PR504

PPU1, DCIU1, FT2

(Source: John Hamley, LeRC)

PPU/DCIU Incoming Test at LeRC (TP 301-87-DP-01)
PPU & DCIU Visual Inspection
PPU/DCIU Continuity/Short test
PPU/DCIU Limited Functional test

Thruster Incoming Test at LeRC (TP 301-57-T-01)
Thruster Visual Inspection

PPU/DCIU Integration Test
PPU & DCIU Integration Test with SPOT-H in Air

Thruster Performance Test with Console
Thruster in Vacuum — 11-14May98(#1)

I Vibration Test @ Acceptance Levels — DCIU in Air
II Vibration Test @ Acceptance Levels — PPU in Air
7,8May98

Vibration Test @ Qual Levels — Thruster in Air — 27,28May98 (Ref TR 503)

Post Vibe PPU & DCIU Test — PPU & DCIU in Air with SPOT
13May98(v1.7)
19May98(v1.8)

Post Vibe Thruster Performance Test — Thruster Test with Console FT in vacuum — 4,5Jun98(#2)

PPU/DCIU/FT Integration — PPU & DCIU in Vacuum, FT in Vacuum
13,14May98 (5 pt. tlm calib.)

Initial Functional Test (TP 301-87-DPT-01) — PPU & DCIU in Vacuum, FT in Vacuum (5 Throttle Points)
19-22May98 w/ SPOT (3 pt. + cycles)

EMI Test — PPU & DCIU

Thermal Vacuum Test @ Accept. Levels — PPU & DCIU in Vacuum, FT in Vacuum — 12-16Jun98 (v1.9)

Final Functional Test — PPU & DCIU in Vacuum, FT in Vacuum (3 Throttle Points) — 17Jun98 (#3) → End

Figure 111. IPS TE Acceptance Test Plan
3-2

4.0' Correlation of PreFlight with Flight Data

One of the primary objectives of the flight validation activity is to verify that the system performs in space as it did on the ground. The parameters of interest to future mission planners are those in the mission throttle table (refer back to Figure 1-1): thrust and mass flow rate as a function of PPU input power. In this section the system power, thrust and mass flow rate behavior in flight will be evaluated in terms of the throttle table.

4.1 Timeline of Flight IPS Activities

Before starting the mission, the operations team conducted an IPS Acceptance Test (IAT) to allow the collection of our operating parameters over the allowed Throttle Table range. Much of that data is compared below to preflight measurements. Once satisfied that the IPS parameter set looked proper, a series of one-week continuous burn periods was started, each termed a NavigationBurn (NBURN) to signify that the on-board navigation software controlled the trajectory parameters. As shown below, thruster power level changed often within each NBURN period – all controlled by the navigation software.

4.2 PPU Power Input Requirements

The PPU input power is determined by the PPU output power (engine power requirement) and the PPU efficiency. The difference between the in-flight engine input power and the BOL throttle table power is shown in Figure 4-1.
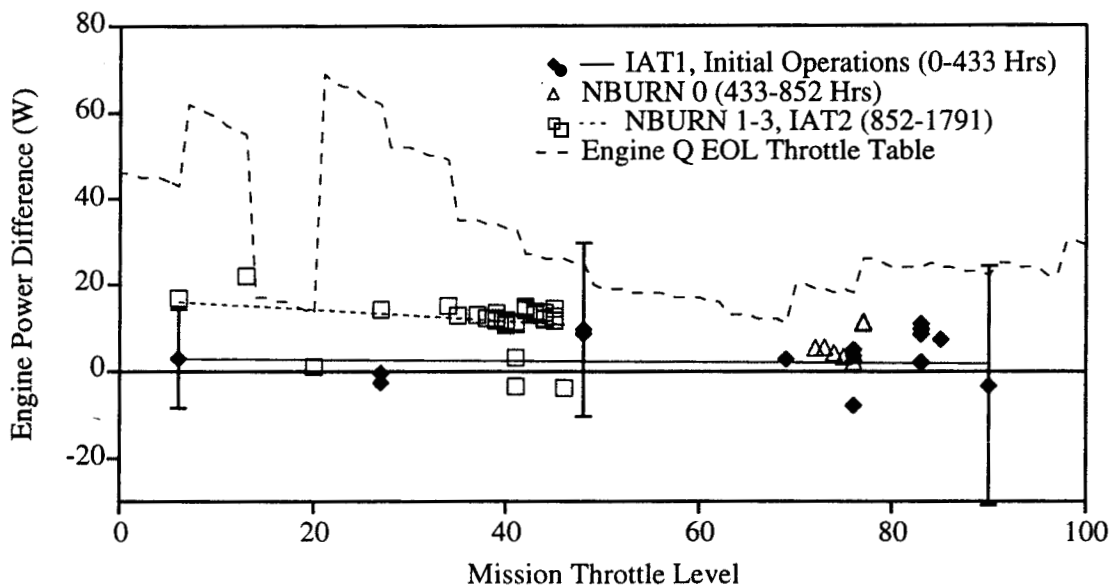
Figure 4-1: Difference between a given engine power level and the throttle table BOL values

These power values are based on the individual power supply current and voltage telemetry readings. The total engine power consumed during the IAT1 throttle test and initial operations differed from the table values by only about 2 W on average, although the uncertainties are much larger than this, as shown by representative error bars on the figure. The engine power requirement increased by 12-15 W with time, however, as the data from NBURNs 1-3 and IAT2 show. This is a normal consequence of engine aging (polk97a, polk99), and the total power at this point in the mission is still less than the EOL power

used in the throttle table, which is represented by the dashed line in Figure 4-1. This increased power demand is due primarily to increased discharge power losses.

In-flight measurements of the PPU efficiency suggest that it is higher than that measured in ground tests, as shown in Figure 4-2.
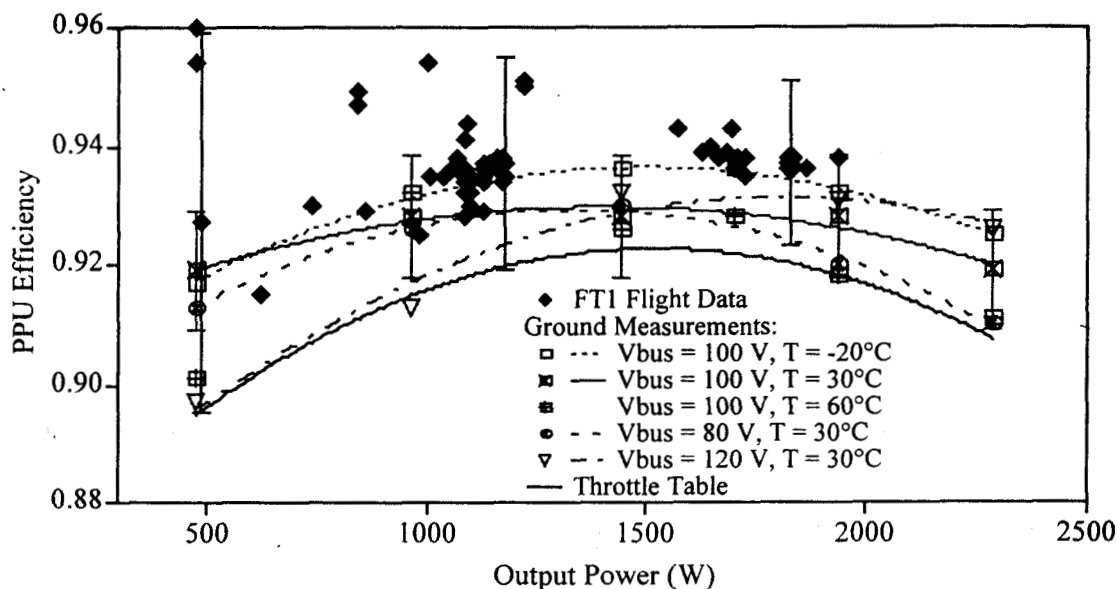
Figure 4-2: In-flight measurements of PPU efficiency compared to ground test **data**

These values are based on the total engine power and PPU high voltage bus current and voltage telemetry with an additional 15 W assumed for the low voltage bus input power. There is no telemetry for the low voltage bus, but ground testing showed a 15 W loss for all conditions. The efficiency is sensitive to the line voltage and the temperature, as the ground data show. The in-flight measurements were taken with line voltages of 95±5 V and baseplate temperatures ranging from 0 to 37°C, so they should be compared with the solid line in the center of the pre-flight data and the highest dashed line. The range of uncertainty in these measurements encompasses the ground test data, but the in-space measurements appear to be higher systematically by about 1 percentage point. This apparent performance gain is not understood and may be due to a systematic error in the ground or flight measurements.

If the PPU efficiency is actually higher than anticipated, it more than offsets the increased output power requirements observed so far in the primary mission. Figure 4-3 displays the difference between the observed PPU input power and the BOL input power from the throttle table.
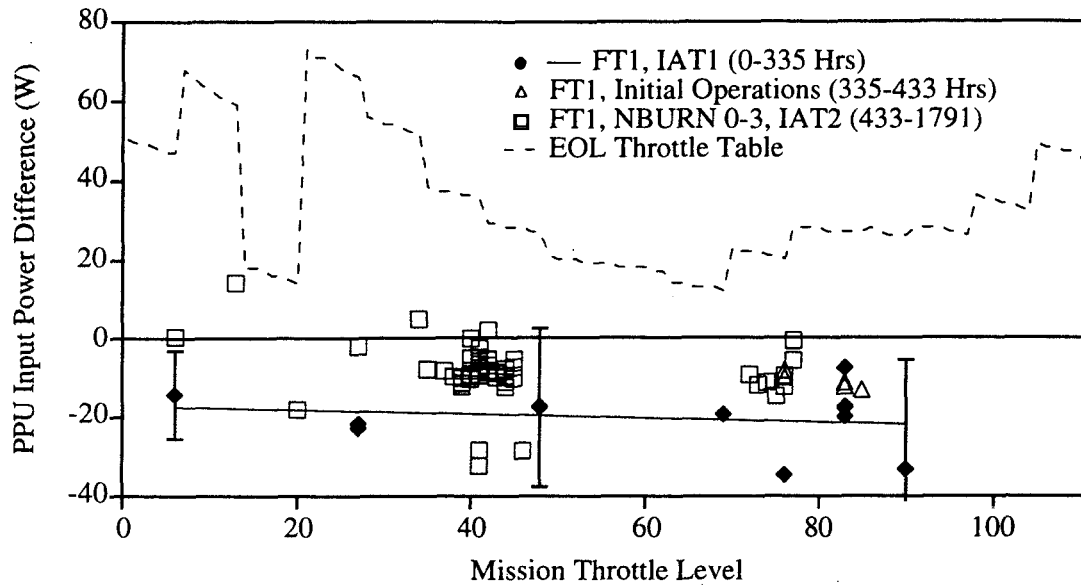
Figure 4-3: Difference between a given PPU input power level and the corresponding throttle table BOL value.

The input power required early in the mission was approximately 20 W lower than expected, because of the higher PPU efficiency. The data from the NBURNs and IAT2 show that the input power is just now approaching the BOL throttle table value.

4.3   IPS Thrust

The acceleration of the spacecraft is measured very accurately from changes in the Doppler shift of the telecommunications signals. With models of the spacecraft mass as a function of time, the Doppler residual data can be used to measure the thrust of the IPS with an uncertainty of less than 0.5 mN. Preliminary thrust measurements have been obtained so far from IAT1, the initial operations and NBURN 0. The flight beam voltage and current values, which determine thrust to a large extent, are slightly different from the setpoints in the table. The flight thrust measurements are therefore compared to the thrust calculated from the actual electrical parameters rather than the table values. The thrust in the mission throttle table is calculated from the engine electrical setpoints,

$$T = \alpha F_t J_b (V_s - V_g)^{1/2} (2M/e)^{1/2} \qquad \text{(Eqn 4-1)}$$

where J_b is the beam current, V_s is the beam power supply voltage, V_g is the coupling voltage between neutralizer common and the facility ground or ambient space plasma, M is the mass of a xenon ion and e is the charge of an electron. The factors α and F_t correct for the doubly-charged ion content of the beam and thrust loss due to non-axial ion velocities [polk97a]. A constant value of 0.98 for F_t based on earlier 30-cm thruster ground tests and a value of α based on a curve fit to centerline double ion current measurements as a function of propellant utilization efficiency in a 30 cm, ring-cusp inert gas [9] were used. Earlier direct measurements of thrust from the LDT agreed well with the calculated value [polk97a,polk99]. More recent measurements with the flight thrusters were somewhat lower than the calculated values for intermediate throttle levels.

The difference in the measured and calculated thrust is shown in Figure 4-4 with curve fits to similar data obtained with a thrust stand in ground tests.
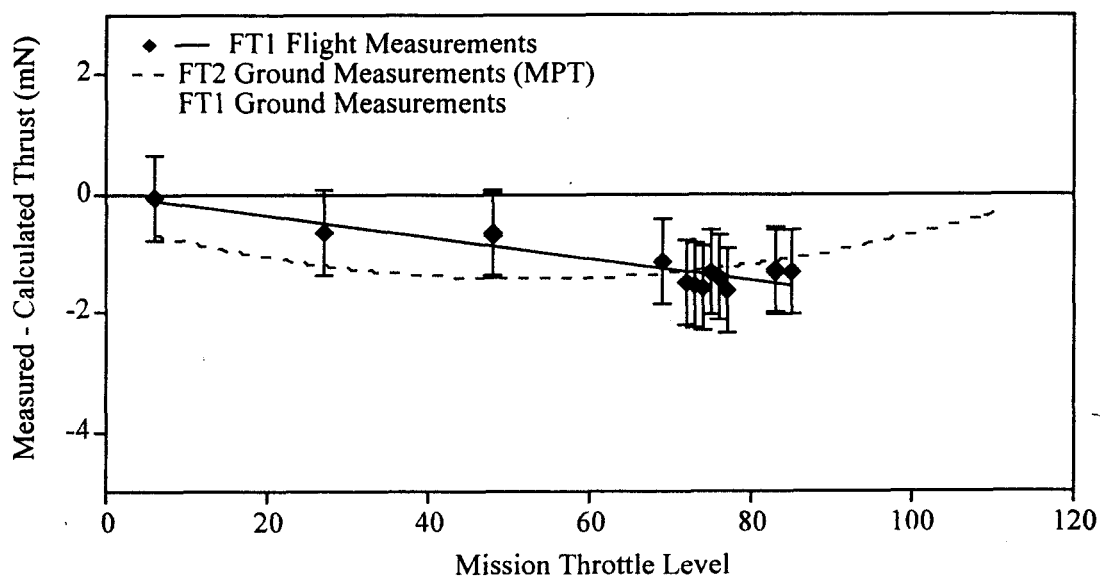
Figure 4-4: Difference between measured and calculated thrust in flight compared to ground measurements.

The ground and flight data agree well with the calculated values at low power levels, but are lower at intermediate powers. The flight data suggest that the difference in true thrust and calculated thrust grows linearly with power, peaking at 1.6 mN lower than expected at mission level 83 (1.82 kWe engine power). The error bars shown in this figure are based on the uncertainty in the measured thrust and do not include errors in the calculated thrust.

This discrepancy may also be due to a systematic error in the flight telemetry, although the agreement with ground data argues against that conclusion. As Equation 4-1 shows, the true thrust might be lower than calculated because of a higher double ion content, greater beam divergence than observed in the previous 30-cm thruster tests, or differences in the coupling voltage in-space compared to ground tests. Additional measurements and analysis will be required to resolve this issue.

Although the actual thrust appears to be slightly lower than expected, at the beginning of the mission the overall system performance was still very close to the BOL throttle table level, in terms of thrust for a given PPU input power. Figure 4-5 shows that at the beginning of the mission the higher PPU efficiency largely compensated for the lower thrust.
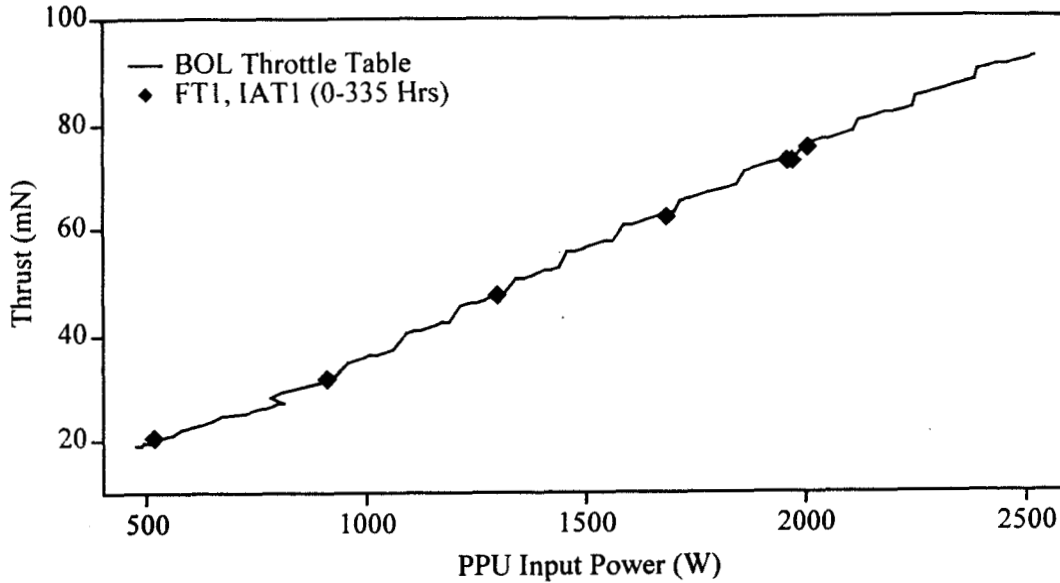
Figure 4-5: Measured thrust as a function of PPU input power compared to throttle table values

In this comparison, the thrust is within 0.5 mN of the table values. The gap between the two widens as the engine wears and the total engine power requirement for a given throttle level grows, however. The PPU input power required for the thrust levels measured during NBURN 0 has exceeded the EOL throttle table power for an equivalent thrust.

4.4   Propellant Flow Rates

The performance of the xenon feed system is discussed in detail in reference 7. In general, the performance has been excellent, although the flow rates are slightly higher than the throttle table values. The mean value of the main flow is 0.05-0.14 sccm (about 0.4 to 1.0 percent) high, while that of the two cathode flows is 0.03 sccm (about 1.0 percent) high. This is in part intentional. As Figure 4-7 shows, the XFS bang-bang regulators result in a sawtooth pressure profile.

Figure 4-7: Example of flow rate throttling.

Throttle Up from Level 83 to 90

Throttle Down From Level 90 to 83

Measured Pressure

Required Pressure

Main Flow Control Device Temperature

Pressure (psia): 84, 82, 80, 78, 76, 74

Temperature (°C): 50, 45, 40, 35, 30, 25

12:30 AM   1:00 AM 12/1/98   1:30 AM   2:00 AM   2:30 AM

Time
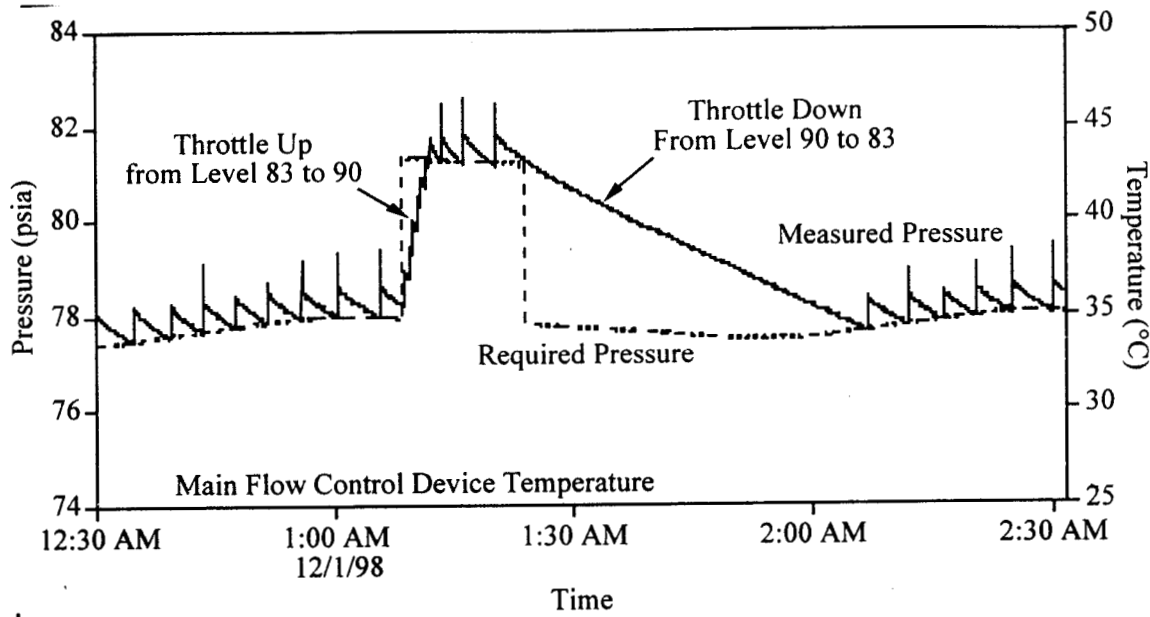
The control system is designed so that the minimum pressure in this sawtooth yields the throttle table flow rate values. In addition to this deliberate conservatism, there is a slight bias in both regulators because one of each of the three pressure transducers on the two plena had a slight offset after launch.

4.5   Overall System Performance

The propulsion system performance can be summarized in terms of specific impulse (Isp) and efficiency. At the beginning of the mission the Isp was about 60 s lower than expected and the engine efficiency was 2 to 2.5 percentage points lower than the throttle table values. The measured performance was still excellent, with a measured efficiency of 0.42 to 0.60 at Isp's ranging from 1960 to 3125 s over an engine throttling range of 478 to 1935 W. The measured mission planning performance parameters are summarized below in Table 4-1.

NSTAR Throttle Level	Mission Throttle Level	PPU Input Power (kW)	Engine Input Power (kW)	Calculated Thrust (mN)	Main Flow Rate (sccm)	Cathode Flow Rate (sccm)	Neutralizer Flow Rate (sccm)	Specific Impulse (s)	Total Efficiency
15	111	2.52	2.29	92.4	23.43	3.70	3.59	3210	0.618
14	104	2.38	2.17	87.6	22.19	3.35	3.25	3157	0.624
13	97	2.25	2.06	82.9	20.95	3.06	2.97	3185	0.630
12	90	2.11	1.94	78.2	19.86	2.89	2.80	3174	0.628
11	83	1.98	1.82	73.4	18.51	2.72	2.64	3189	0.631
10	76	1.84	1.70	68.2	17.22	2.56	2.48	3177	0.626
9	69	1.70	1.57	53.0	15.98	2.47	2.39	3136	0.618
8	62	1.56	1.44	57.8	14.41	2.47	2.39	3109	0.611
7	55	1.44	1.33	52.5	12.90	2.47	2.39	3067	0.596
6	48	1.32	1.21	47.7	11.33	2.47	2.39	3058	0.590
5	41	1.19	1.09	42.5	9.82	2.47	2.39	3002	0.574
4	34	1.06	0.97	37.2	8.30	2.47	2.39	2935	0.554
3	27	0.93	0.85	32.0	6.85	2.47	2.39	2836	0.527
2	20	0.81	0.74	27.4	5.77	2.47	2.39	26.71	0.487
1	13	0.67	0.60	24.5	5.82	2.47	2.39	.2376	0.472

0	6	0.53	0.47	20.6	5.98	2.47	2.39	1972	0.420

Table 4-1: Flight throttle table of parameters used in mission analysis.

The flight team is in the process of refining the BOL table on board the spacecraft because the navigation manager uses calculated thrust each week to predict the next NBURN commanded levels.

5.0   Summary

The NSTAR Project accumulated 12918 hours of operation on a variety of EM thrusters before the DS1 launch date (excluding the ELT and the cathode erosion test), all with the intention of validating the NASA thruster design in as careful a manner as possible. We accomplished this purpose by testing to gradually longer durations, analyzing the physical results whenever possible, and limiting design articles to single changes before gathering further results during issue investigations. This is a measure of the careful logic and the depth of the development program before we were confident of the design for the DS1 mission. That testing background led to high confidence as the ELT started that it would be a test to completion.

Similarly, total test time on the flight thrusters was 125.9 hours before the launch. The additional 7400 hours accumulated on FT1 and FT2 to date are testimony to a carefully planned test program.

Time continues to accumulate in the ELT as we march toward the Project goal of 125 kg of xenon throughput for the flight spare thruster, which is equivalent to 150% of the original lifetime goal. We are very confident now that the true lifetime will be much higher and are considering extending the ELT past 125 kg if conditions seem appropriate.

References

1) AIAA 99-2972, "The NSTAR Ion Propulsion System for DS1", Christensen, Benson, Bond, Gallagher, Matranga, 20 Jun 99.
2) AIAA 99-2270, "A Synopsis of Ion Propulsion Development Projects in the US: SERT I to DS1", Sovey, Rawlin, Patterson, 20 Jun 99.
3) AIAA 95-2516, "2.3kW Ion Thruster Wear Test", Patterson, et al, 10 Jul 95.
4) AIAA 96-2717,"1000 Hour Wear Test of the NSTAR Ion Thruster", Polk et al, 1 Jul 96.
5) AIAA 99-2446,"8200 Hour Wear Test of the NSTAR Ion Thruster", Polk et al, 20 Jun 99.
6) AIAA 97-3387, "Effect of Engine Wear on Performance in the NSTAR 8000 Hour Ion Engine Endurance Test", Polk et al, 6 Jul 97.
7) AIAA 99-2273, "Post-Launch Performance Characterization of the Xenon Feed System on DS1", Ganapathi, Engelbrecht, 20 Jun 99.
8) AIAA 99-2274, "Validation of the NSTAR Ion Propulsion System on the DS1 Mission: Overview and Final Results", Polk et al, 20 Jun 99.
9) AIAA 94-2849, "NASA 30 cm Ion Thruster Development Status", Patterson, Haag, Rawlin, Kaussmaul, 27 Jun 94.

Figures

Tables